

## **A METHOD OF DETECTING ZOMBIE BREAKPOINTS**

### **FIELD OF THE INVENTION**

The present invention relates to the debugging of software and computer programs and

5 more particularly to the use of breakpoints in debugging processes.

### **BACKGROUND**

Debugging is a process of detecting and locating errors or events in computer programs

and other software with a view to eliminate such errors or events. Debugging may also

10 involve the step of eliminating such errors. The debugging process is implemented using  
a debugger, which is a computer program or programs for detecting, tracing, and  
eliminating errors or events in computer programs, and other software. The latter are each  
referred to hereinafter as the “debugge”.

15 A breakpoint is a point in a computer program or software where execution may be  
halted, normally at a place that is convenient for restarting execution of the program or  
software (i.e., the debuggee) from that point. That is, breakpoints are events deliberately  
inserted or “planted” in a debuggee by a debugger to receive control when the debuggee  
reaches a certain point during execution of the debuggee. At that point, the debugger needs  
20 access to the state of the debuggee (perhaps with the ability to change that state), and either  
to resume or terminate execution of the debuggee.

If a breakpoint is applicable only in the context of a specific process, the breakpoint is  
considered to be a local breakpoint. The same applies for plural breakpoints. Application

25 debuggers generally use local breakpoints.

In contrast, global breakpoints are breakpoints active across all processes executing in a  
computer system, where two or more processes may use the same code segment. In other  
words, global breakpoints are applicable in all instances of a program or software code

30 segment. If a global breakpoint event occurs, the debugger can instrument the debugged  
code irrespective of the process running that code. In this case, the concept of one  
debuggee does not apply, and the target is not the process being debugged but the code that  
is being executed. Kernel-level debuggers and some code-instrumentation tools use  
global breakpoints, because the focus is on the code being debugged / instrumented and

not on any specific process context.

Breakpoints are placed by a mechanism that enables the determination of whether a breakpoint condition is present at any time. Some common techniques for placing

5 breakpoints are:

- inserting a special instruction at breakpoint location,
- inserting an illegal instruction at breakpoint location, and
- using a special debug register at breakpoint location.

Breakpoints are typically placed using a special breakpoint instruction available on most

10 processor architectures.

Implementing breakpoints for debugging multi-threaded applications under multi-processing environments presents a number of problems and detecting zombie breakpoints is one of the most difficult.

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The term “zombie breakpoint” appears in the context of a race condition between a breakpoint hit in one thread/processor and the simultaneous removal of the same breakpoint in the context of another thread/processor. By the time the breakpoint handler gets to process the breakpoint hit, the breakpoint has been removed without any trace by another thread/processor and is no longer “owned” by the debugger. This leads to a situation, where the breakpoint handler thinks that the breakpoint event happened due to some other external cause and incorrectly passes the breakpoint back to the operating system, which treats the breakpoint as an unhandled exception.

20 Thus, a need exists for an improved method of detecting zombie breakpoints.

## SUMMARY

In accordance with a first aspect of the invention, a method of detecting one or more zombie global breakpoints for debugging computer software is disclosed. The method

30 includes the steps of:

checking a breakpoint data structure to determine if a breakpoint known to a debugging process is at an address where a breakpoint fired;

if a known breakpoint cannot be determined at the address, verifying if a breakpoint condition continues to exist at the address where the breakpoint fired; and

if the breakpoint condition does not exist, identifying the breakpoint as a zombie breakpoint.

The verifying step may include the step of checking that a special breakpoint instruction exists at the address, being the exception location. Further, the verifying step may include the step of checking that an illegal breakpoint instruction exists at the address, being the exception location. Still further, the verifying step may include the step of checking that the address, being the exception location, is present in a special debug register.

5       10 Preferably, physical settings for causing a breakpoint exception at a particular location are detectable from a breakpoint handler. Breakpoint removal logic is preferably provided that lifts a physical breakpoint instruction from a breakpoint location before removing a breakpoint entry from the breakpoint data structure of the debugging process.

15       20 In accordance with a second aspect of the invention, a computer-implemented apparatus for detecting one or more zombie global breakpoints for debugging computer software is disclosed. The apparatus includes:

- a central processing unit for executing the computer software;
- memory for storing at least a portion of the computer software;

25       25 a module for checking a breakpoint data structure to determine if a breakpoint known to a debugging process is at an address where a breakpoint fired;

- a module for, if a known breakpoint cannot be determined at the address, verifying if a breakpoint condition continues to exist at the address where the breakpoint fired; and
- a module for, if the breakpoint condition does not exist, identifying the breakpoint as a zombie breakpoint.

In accordance with a third aspect of the invention, a computer program product having a computer readable medium having a computer program recorded therein for detecting one or more zombie global breakpoints for debugging computer software is disclosed. The

30       35 computer program product includes:

- a computer program code module for checking a breakpoint data structure to determine if a breakpoint known to a debugging process is at an address where a breakpoint fired;

a computer program code module for, if a known breakpoint cannot be determined at the address, verifying if a breakpoint condition continues to exist at the address where the breakpoint fired; and

a computer program code module for, if the breakpoint condition does not exist,  
5 identifying the breakpoint as a zombie breakpoint.

#### **BRIEF DESCRIPTION OF THE DRAWINGS**

A small number of embodiments are described hereinafter, in which:

Fig. 1 is a flow diagram illustrating a process for identifying a zombie breakpoint in  
10 accordance with the preferred embodiment of the invention; and

Fig. 2 is a block diagram illustrating a general purpose computer, with which  
embodiments of the invention can be practiced.

#### **DETAILED DESCRIPTION**

15 A method, an apparatus, and a computer program product are disclosed for identifying or detecting one or more zombie breakpoints for debugging computer software. In the following description, numerous details are set forth including particular operating systems. It will be apparent to one skilled in the art, however, that the present invention may be practised without these specific details. In other instances, well-known features  
20 are not described in detail so as not to obscure the present invention.

In the following description, components of the zombie breakpoint identification system are described as modules. A module, and in particular its functionality, can be implemented in either hardware or software. In the software sense, a module is a process,  
25 program, or portion thereof, that usually performs a particular function or related functions. In the hardware sense, a module is a functional hardware unit designed for use with other components or modules. For example, a module may be implemented using discrete electronic components, or it can form a portion of an entire electronic circuit such as an Application Specific Integrated Circuit (ASIC). Numerous other possibilities exist.  
30 Those skilled in the art will appreciate that the system can also be implemented as a combination of hardware and software modules.

The embodiments of the invention provide a breakpoint-discrimination process (whether implemented by part of the operating system kernel or by a separate debugger) to deal  
35 with the following problem. In the following discussion, the term "debugger" is used to

refer to the part of an operating system kernel that performs the functions of a debugger or a separate debugger module. Assuming a single instance of a debugger with some kind of serialisation ensuring that only one thread is actually “in” the debugger at any time, the following situation may arise when zombie breakpoint discrimination has to be performed

5 by the debugger itself:

1. Threads A and B hit a breakpoint at nearly the same time. At the system level, these are simply two reportable events.
2. One of the threads (e.g. A) gains entry to the debugger, while the other thread (B) remains pending, waiting for the debugger to finish with event A.
- 10 3. Event A is analysed and reported to be a breakpoint.
4. The user decides to cancel the breakpoint and resumes thread A.
5. Event B is then reported to the debugger.
6. Event B is analysed, but there is no breakpoint anymore and indeed the interrupt information may be inconsistent.

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This is a tricky and subtle problem that is not addressed in other debugging instrumentation tools. If the debugger does not detect the zombie breakpoint condition correctly, the operating system incorrectly assumes the breakpoint exception to be an unhandled exception and takes the default action, which usually results in the debuggee 20 terminating. This is a significant problem that needs to be solved to implement a debugger that can be used to debug highly timing-sensitive multi-threaded applications correctly under all circumstances.

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In the embodiments of the invention, breakpoint-discrimination logic in a debugger is responsible for looking up breakpoint data structures to determine if there is a breakpoint known to the debugger at the address where the breakpoint is fired. If this routine cannot find a known breakpoint, the debugger recognises that this may be a zombie breakpoint and does just one more check: verify if the breakpoint condition is still at the address where the breakpoint is fired. If the breakpoint is not there, a zombie breakpoint is 30 identified and handled accordingly. On the other hand, if the breakpoint instruction is still at the breakpoint location, this breakpoint exception must have been meant for a different facility and is not treated as a relevant breakpoint.

The exact method of checking for a breakpoint condition as mentioned above depends on

the way in which breakpoints are inserted in the first place. This could be by any of the following:

- check that the special breakpoint instruction is still at the exception location,
- check that the illegal instruction is still at the exception location, and
- check that the exception location is still present in the special debug register.

5 The main, if not only, requirement for this method to work is that the physical settings for causing a breakpoint exception at a particular location be detectable from a breakpoint handler.

10 For this approach to work smoothly, the breakpoint removal logic takes care to first lift the physical breakpoint instruction from the breakpoint location before removing the breakpoint entry from the data structures of the debugging.

#### Linux (on Intel x86) Specific Implementation Details

15 The preferred embodiment utilises an Intel x86 platform for the sake of simplicity. The embodiments are similarly applicable to other processor architectures. The following description of the preferred embodiment is from the point of view of the debugger/tool utilising the solution described above:

20       a. Apply global breakpoints by inserting a special breakpoint instruction (INT3) at the desired locations.  
          b. Assuming two threads, executing on different processors, hit the same INT3 at the same time (events A and B).  
          c. Assume Event A enters the breakpoint discrimination logic first.  
25       d. Event A is determined to be a breakpoint and is reported (handle Event A).  
          e. User removes the breakpoint being handled (INT3) while handling Event A.  
          f. Next, Event B enters the breakpoint discrimination logic.  
          g. Event B is not considered a breakpoint as the breakpoint has been removed in step e above.  
30       h. Verify if there is an INT3 instruction at the trapping location.  
          i. The INT3 Instruction is not there as step e above removed the breakpoint.

Thus, event B is due to a breakpoint that has been removed after being hit (i.e., a zombie). Once a zombie breakpoint is detected, the breakpoint can be handled according to a policy

defined by the debugger to handle zombie breakpoints.

Fig. 1 illustrates the process for detecting zombie breakpoints according to the preferred embodiment. With respect to the process 100, a time line is indicated. The breakpoint instruction, i.e., INT3, is contained in a code module 120 that is being executed on two processors or threads 0, 1. At a specified point in time, a breakpoint is fired. Event A is the breakpoint exception for thread 0, while event B is the breakpoint exception for thread 1. In step 122, a do\_int3 process is executed. This is done in parallel with the do\_int3 module 110 for event B. The module do\_int3 110, 122 is the breakpoint exception 10 handler in the Linux Kernel on Intel platforms. However from step 122, in step 124, event A enters the debugger. Meanwhile in parallel step 112, the processing of event B is blocked waiting entry of the debugger.

In the time line, after step 124, breakpoint discrimination logic processes event A. The identified breakpoint is then provided to a breakpoint processing module 128. In step 130, the breakpoint is removed for event A. Processing then continues in step 132, in which the debugger is left. A dashed line 150 shown in Fig. 1 is meant to relate the timing of event B to that of event A. The steps to the right of dashed line 150 occur after step 112 and after step 132. As described earlier, after step 122, processing of event B 20 was blocked waiting entry of the debugger. After step 132 for event A is performed, event B can then enter the debugger in step 114 from step 112. From step 114, breakpoint discrimination logic is applied to event B in step 116. However step 116 does not find the relevant breakpoint. This is because the breakpoint was removed in step 130 for event A. Processing after step 116 enters the zombie breakpoint detection logic 140. In particular, 25 processing continues at step 142.

In step 142, a check is performed to locate the instruction INT3 at the breakpoint location. Processing then continues at decision step 144. In decision block 144, a check is made to determine if there is an INT3 instruction at the breakpoint location. If decision block 144 30 returns false (no), a zombie breakpoint 146 is determined. Otherwise, if decision block 144 returns true (yes), a determination is made that a breakpoint of some other debugger has been found.

#### Special Situations

The applicability of the embodiments is discussed for cases even when the debugger utilising the technique operates in the presence of other debugging tools that may utilize similar techniques for placing breakpoints.

5 If another debug facility, running on another processor, puts an INT3 instruction at the same location in the meanwhile (after block 130 and before block 114 in the time line as shown in Fig. 1), an INT3 is then seen at the breakpoint location (in the decision block 144 in Fig. 1), though not the one placed by the relevant debugger. Then the correct conclusion is made: that this INT3 is due to a breakpoint placed by another debug

10 facility, and normal processing of the operating system's breakpoint exception handler do\_int3 will let the correct debug facility handle the breakpoint.

Another debug facility running on another processor may put an INT3 instruction at the same location in the meanwhile (i.e. after block 130 and before block 114), hit the  
15 breakpoint and then remove the breakpoint again. All of this may occur before block 114 is reached. If so, the relevant debugger arriving at step 144 decides there is no INT3 instruction at the breakpoint location and that this is a zombie breakpoint. Again, this is the correct thing to do under the circumstances.  
20 Thus, the embodiments work correctly even in the presence of other debug facilities.

The embodiments advantageously provided a simple method of detecting zombie breakpoints in the context of global breakpoints under a multi-processor environment.

25 The embodiments of the invention are preferably implemented using a general-purpose computer. In particular, the processing or functionality of Fig. 1 can be implemented as software, or a computer program, executing on the computer. The method or process steps for detecting one or more zombie global breakpoints for debugging computer software are effected by instructions in the software that are carried out by the computer.

30 The software may be implemented as one or more modules for implementing the process steps. A module is a part of a computer program that usually performs a particular function or related functions. Also, as described hereinbefore, a module can also be a packaged functional hardware unit for use with other components or modules.

In particular, the software may be stored in a computer readable medium, including the storage devices described below. The software is preferably loaded into the computer from the computer readable medium and then carried out by the computer. A computer program product includes a computer readable medium having such software or a

5 computer program recorded on it that can be carried out by a computer. The use of the computer program product in the computer preferably effects advantageous apparatuses for detecting one or more zombie global breakpoints for debugging computer software.

Preferably, a computer system 200 shown in Fig. 2 includes the computer 250, a video  
10 display 210, and input devices 230, 232. In addition, the computer system 200 can have any of a number of other output devices including line printers, laser printers, plotters, and other reproduction devices connected to the computer 250. The computer system 200 can be connected to one or more other computers via a communication interface using an appropriate communication channel 240 such as a modem communications path, a  
15 computer network, or the like. The computer network 220 may include a local area network (LAN), a wide area network (WAN), an Intranet, and/or the Internet.

The computer 200 itself preferably includes a central processing unit(s) 266 (simply referred to as a processor hereinafter), a memory 270 which may include random access  
20 memory (RAM) and read-only memory (ROM), input/output (IO) interfaces 264, 272, a video interface 260, and one or more storage devices 262. The storage device(s) 262 can include one or more of the following: a floppy disc, a hard disc drive, a magneto-optical disc drive, CD-ROM, magnetic tape or any other of a number of non-volatile storage devices well known to those skilled in the art. Each of the components is typically  
25 connected to one or more of the other devices via a bus 280 that in turn can consist of data, address, and control buses.

The video interface 260 is connected to the video display 210 and provides video signals from the computer for display on the video display 210. User input to operate the  
30 computer can be provided by one or more input devices 230, 232. For example, an operator can use a keyboard 230 and/or a pointing device such as the mouse 232 to provide input to the computer.

The foregoing system is simply provided for illustrative purposes and other configurations

can be employed without departing from the scope and spirit of the invention. Computers with which the embodiment can be practiced include IBM-PC/ATs or compatibles, one of the Macintosh (TM) family of PCs, Sun Sparcstation (TM), a workstation or the like. The foregoing are merely examples of the types of computers with which the embodiments of

5 the invention may be practiced. Typically, the processes of the embodiments, are resident as software or a program recorded on a hard disk drive as the computer readable medium, and read and controlled using the processor. Intermediate storage of the program and intermediate data and any data fetched from the network may be accomplished using the semiconductor memory, possibly in concert with the hard disk drive.

10 In some instances, the program may be supplied to the user encoded on a CD-ROM or a floppy disk, or alternatively could be read by the user from the network via a modem device connected to the computer, for example. Still further, the software can also be loaded into the computer system from other computer readable medium including

15 magnetic tape, a ROM or integrated circuit, a magneto-optical disk, a radio or infra-red transmission channel between the computer and another device, a computer readable card such as a PCMCIA card, and the Internet 220 and Intranets including email transmissions and information recorded on websites and the like. The foregoing are merely examples of relevant computer readable mediums. Other computer readable mediums may be

20 practiced without departing from the scope and spirit of the invention.

Finally, while the preferred embodiment is implemented using the Linux operating system, it will be appreciated by those skilled in the art in view of this disclosure that the embodiments of the invention can be practiced with other operating systems as well.

25 Further, even though the embodiment is described in the context of the Intel x86 architecture, embodiments of the invention can be applied to other processor architectures, as long as the physical settings for causing a breakpoint exception at a particular location can be detected explicitly within a breakpoint handler.

30 In the foregoing manner, a method, an apparatus, and a computer program product for detecting one or more zombie global breakpoints for debugging computer software are disclosed. While only a small number of embodiments are described, it will be apparent to those skilled in the art in view of this disclosure that numerous changes and/or modifications can be made without departing from the scope and spirit of the invention.